Probabilistic seismic risk analysis of existing buildings in regions with moderate seismicity

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Probabilistic seismic risk analysis of existing buildings in regions with moderate seismicity

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ABSTRACT:
In 2004, Switzerland started to apply an approach based on risk for the seismic assessment of existing buildings. In this innovative approach, the concept is to guarantee an acceptably low individual risk coupled with an evaluation of the efficiency of the retrofitting measures. It includes a relationship derived from empirical data between the compliance factor and the individual risk. The compliance factor can be deterministically computed from usual analytical seismic assessment methods, as the ratio between the capacity and the requirement of the current codes for new buildings.
However, it is also possible to proceed probabilistically by computing the individual risk using probabilistic seismic hazard assessment, site response, fragility curves of the structure and probability of death depending on the damage grade. Comparisons between these computations on a typical Swiss building and the values proposed in the Swiss approach show significant differences and raise important issues for earthquake engineering.
The first issue is the real meaning of the compliance factor when computed with force-based or displacement-based methods. Moreover, the collapse probability of a building having a compliance factor of 1 for the design ground motion is difficult to determine. The second issue concerns the degree of conservatism in the different parameters used, hazard and vulnerability. In conclusion, the probabilistic analysis of existing buildings, even with all the currently available tools is not straightforward.

Keywords: Individual risk, seismic hazard assessment, fragility curves, compliance factor, existing buildings

1. INTRODUCTION

The seismic analysis of existing buildings should ideally be performed probabilistically based on the risk (economic, human lives…) of the study-structure for the earthquake hazard. It could then be a decision-making aid for authorities and engineers to decide whether a structure should be retrofitted or not. This is what suggests the Swiss Pre-Standard SIA 2018 (SIA, 2004) by proposing a decision scheme based on risk and a cost-benefit methodology.
In the field of earthquake engineering (Pinto, 2001; Hadjian, 2002; McGuire 2004), reliability analysis was especially developed with Performance-based design (PBD), even if full hazard assessment is generally not performed in PBD. New approaches such as Consequence Based Engineering approach (Abrams et al., 2002) were also proposed. Ellingwood and Wen (2005) proposed such a methodology for Mid-America, emphasizing that in low seismicity areas, seismic risk is often higher than it is perceived. Viallet (2007) estimated the risk of a building in France following the design code in order to show that its risk was acceptable. Concerning the assessment of existing structure, McGuire (2004) proposes a general methodology for risk-based retrofitting and insurance decisions, Kappos and Dimitrakopoulos (2008) estimated the risk of the building stock of a city in Greece to estimate if a strengthening at a large scale was feasible. Park et al. (2009) and Williams et al. (2009) also proposed probabilistic methodologies based on risk to decide whether a structure should be retrofitted or not. Moreover, Romao et al. (2008) proposed an integrated method accounting for both hazard and vulnerability to directly compute the risk for assessment purposes. It should be noticed that all these methods are probabilistic, relatively complex and applicable in practice only by experts.
On the contrary, the Swiss methodology (SIA, 2004), even though based on a probabilistic framework,

was designed for a practical use by engineers. For that purpose, it is based on a relationship between the risk and a deterministic parameter, the compliance factor, easily computed using classical engineering approaches. Such a link between probabilistic and deterministic parameters, necessary for a practical use, raises some important issues.
This relationship was initially developed using an Intensity-based hazard assessment, EMS 98 (Grünthal et al., 1998) and expert judgement. However, probabilistic seismic hazard assessment (PSHA) based on spectral characteristics and mechanical vulnerability curves are now standard tools in risk assessment. It should be therefore possible to compute the risk of particular buildings and enhance the empirical relationship of SIA 2018. This computation is however not straightforward. Is our knowledge (PSHA, vulnerability curves) good enough to use risk as a decision-making aid for existing buildings? What are the largest sources of uncertainties, of conservatism in these assessments?
The basic concepts of the SIA 2018 are first detailed, then, the methodology to compute the risk using available probabilistic tools is presented. It is finally applied to an existing URM building in Switzerland studied in more details in Oropeza (2010a) and the results are discussed.

2. SIA 2018 CONCEPTS

The SIA 2018 Pre-Standard (SIA, 2004), that will evolve in a Swiss Standard in the next years, is based on the individual risk, i.e. on the risk for a person to die in the considered building due to an earthquake. After comparisons with other types of accepted individual risks, it has been decided that the individual risk for earthquake safety in Switzerland should not exceed 10^{-5} per year. This corresponds to the risk of doing 10000 km by train each year. However, it is not realistic to ask an engineer evaluating the earthquake safety of a building to perform a probabilistic risk analysis. Therefore, the SIA 2018 links the individual risk to a deterministic value computed commonly by the engineer, the compliance factor α_{eff} defined as the ratio between the level of earthquake loading when reaching the structural capacity and the level of earthquake loading prescribed by the building codes for new buildings (SIA, 2004; Vogel and Kölz, 2005).
The link between the individual risk RF and the compliance factor α_{eff} was proposed by Kölz (2004) and Vogel and Kölz (2005) based on an intensity-based hazard assessment, the EMS98 (Grünthal et al., 1998) vulnerability classes and expert opinions to estimate the compliance factor for each vulnerability class (forced-based assessment). The resulting curve is displayed on Fig. 2.1.

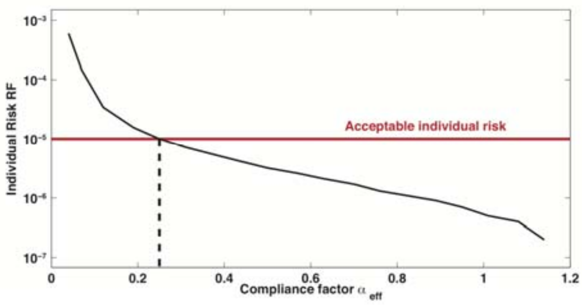

Figure 2.1. Relationship between the individual risk and the compliance factor (from Kölz and Duvernay, 2005)

The earthquake loading (capacity and code prescription) can either be computed in force (conventional seismic analysis) or in displacement (performance-based seismic analysis). Originally, the force-based approach has been used in the design of the SIA 2018 method, but more realistic displacement-based approaches are more and more used because they generally lead to higher compliance factors. They may however not be compatible with the original definition of the SIA 2018 approach.

SIA 2018 curve of Fig. 2.1 (Kölz and Duvernay, 2005) links a probabilistic concept (RF) with a deterministic value (α_{eff}), which raises some important issues. What should be the probability of collapse of a structure of a compliance factor of 1 in case of the design earthquake? This issue is crucial when one wants to define the vulnerability in terms of fragility curves, showing the probability of exceeding a given damage grade (e.g. collapse) as a function of the seismic demand. Non-linear static procedures (push-over), commonly used to compute fragility curves (e.g. FEMA, 2003), may indeed be similar to displacement-based procedures used to compute the compliance factor. For instance, it could be assumed that this example building with α_{eff}=1 has a 50% chance (median of the fragility curve) to partially collapse in case of the design earthquake happens.

3. PROBABILISTIC COMPUTATION OF RISK

Considering that now the hazard is estimated through probabilistic hazard assessment (PSHA) and the vulnerability of structures as vulnerability curve, it is obvious that the individual risk should be computed fully probabilistically using these new tools. It is therefore proposed to reconstruct the SIA 2018 curve (Fig. 2.1) using these updated techniques.

3.1 Hazard

Probabilistic Seismic Hazard Assessment (PSHA) of Switzerland (Giardini et al., 2004; Wiemer et al., 2009) has been computed using a logic-tree approach. As generally done for moderate seismicity countries, homogeneous seismic zones have been considered and no particular seismogenic faults. The hazard curves provide the probability of exceedance of spectral accelerations at 5 Hz S_a(5Hz) (plateau) with a 5% damping for a rock with a shear-wave velocity V_s of 1500 m/s (Fig. 3.1). Uncertainties are also provided in terms of 16% and 84% percentiles probabilities. The values are given up to a probability of 10^{-4}, i.e. a return period of 10000 years. This value is probably already larger than what can be said with confidence, but, in areas with moderate seismicity, the reached accelerations at these return periods are still quite weak and higher values may be necessary to compute the total risk. For the computations, the Probability Density Function (PDF) (noted $p(S_a)$ hereafter) instead of the exceedance curve is needed. To compute it, one should just remark that the complementary probability of the exceedance curve is the Cumulative Density Function. Therefore, the PDF is the opposite of the derivative of the exceedance curve (Hadjian, 2002).

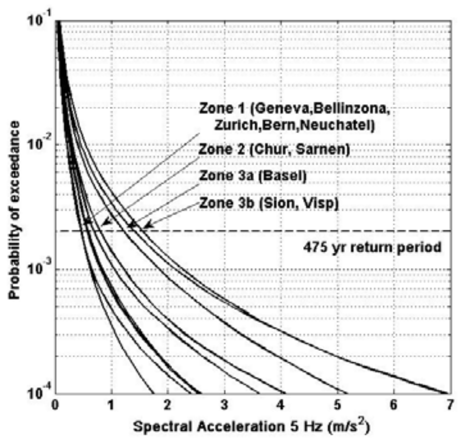

Figure 3.1. Hazard curves proposed in Giardini et al. (2004) for Switzerland

The surface effects should then be taken into account since buildings are generally built on soils with a low shear-wave velocity and not only rock. For that purpose, it has been chosen to derive the Peak Ground Acceleration (PGA) from the spectral acceleration at 5 Hz and to use the spectral shapes given in the Eurocode 8 (identical to Swiss Codes). In this way, the PGA value may be underestimated compared to the spectral demand that is estimated "without bias". This procedure has been already used in the Swiss Code to estimate the PGA map and therefore the seismic demand. In the Swiss Code the PGA a_g was derived for a B ground class (V_s=400-800 m/s) (Wenk and Lestuzzi, 2003):

$$a_g = \frac{3.5 * S_a(5Hz) + 2.5 * S_a(10Hz)}{2} \frac{1}{2.5} \frac{1}{1.2} \tag{3.1}$$

However, the spectral acceleration at 10 Hz is not provided by the Swiss Seismological Service. Considering only the amplification between stiff rock and B soil at 5 Hz of 3.5, i.e. only the first part of the average, this leads to the relationship:

$$a_g = 1.2 * S_a(5Hz) \tag{3.2}$$

Roten (2007) showed that the amplification in the Rhone valley in term of response spectrum at 5 Hz was around 5 for C class sites. This leads to greater values $a_g = 1.7 * S_a(5Hz)$. This value is used as an upper bound for the computations.
Moreover, the use of the code response spectrum shapes is itself conservative. It would be necessary to use amplification functions from the spectral acceleration at 5 Hz on the rock to derive an average, and not envelope, response spectra for the different ground classes.
Hazard assessment is always enhanced. In the forthcoming versions of the PSHA, ground motion prediction equations accounting for upper layer properties (e.g. V_{s30}) may directly provide spectral accelerations for all frequencies and all soil classes.

3.2 Vulnerability

In risk assessment, the vulnerability of structures is represented probabilistically using the fragility curves, generally modelled as lognormal cumulative density functions. They commonly give the probability of exceedance of each damage grade as a function of the spectral displacement at the period and damping of the structure (FEMA, 2003, Milutinovic and Trendafiloski, 2003). Oropeza et al. (2010a,b) proposed fragility curves for Swiss unreinforced masonry (URM) structures using a displacement-based method to estimate the building capacity and following the EMS98 damage scale. In the computation of fragility curves, the attention was paid to use the elastic spectral displacement in ordinate (Michel et al., 2009) and not the inelastic one as done in HAZUS (FEMA, 2003) or Risk-UE (Milutinovic and Trendafiloski, 2003). The uncertainties on these estimations were not explicitly computed. An default uncertainty value of ±10% on the frequencies and ±30% on the fragility curve medians was used here to compute a maximum and minimum risk value.

3.3 Individual risk

The yearly probability of exceedance of the damage grade i can therefore be computed as follows (Hadjian, 2002):

$$p_{d_i} = \int_0^{\infty} p(S_a) \, p_{FCi}\left(\frac{a_g(S_a) * S_a^{SIA-GC}(f, 5\%)}{4\pi^2 f^2} \right) dS_a \tag{3.3}$$

with $p(S_a)$ the PDF of the hazard, p_{FCi} the i^{th} fragility curve, $S_a^{SIA-GC}(f, 5\%)$ the spectral acceleration shape (i.e. PGA=1 m/s^2) in the Swiss codes for a ground class GC at the frequency f of the structure and for 5% damping.

The probability of dying in case of earthquake depends on the probability of damage grades 4 and 5 EMS98 (Coburn et al., 1992; Kölz and Duvernay, 2005). The individual risk RF is then computed as follows:

$$RF = \int_0^\infty p(S_a) \left[\begin{array}{l} x\big(a_g(S_a)\big) p_{FC4}\left(\frac{a_g(S_a) * S_a^{SIA-GC}(f,5\%)}{4\pi^2 f^2} \right) \\ +\Big(y\big(a_g(S_a)\big) - x\big(a_g(S_a)\big)\Big) p_{FC5}\left(\frac{a_g(S_a) * S_a^{SIA-GC}(f,5\%)}{4\pi^2 f^2} \right) \end{array} \right] dS_a \tag{3.4}$$

with x and y representing the death probability in a structure in damage grade 4 and 5, respectively. These values are estimated from event feedback and depend on the ground acceleration (Kölz and Duvernay, 2005): the greater the ground acceleration, the more difficult to escape the collapsing building, the higher the death probability. Maximum, minimum and average values of x and y were used as given in Kölz and Duvernay (2005): x varies from 1 to 6% at 0.4 m/s^2 up to 2 to 12% at 4 m/s^2 and y varies from 10 to 30% at 0.4 m/s^2 up to 20 to 60% at 4 m/s^2. A logarithmic regression was used in between these values. These values are higher than the one found in HAZUS (FEMA, 2003).

4 CASE STUDIES

4.1 Data

The aforementioned methodology is applied to a typical existing URM buildings in Switzerland (Tab. 4.1.). It is made of stone masonry walls with stiff floors. Assuming this existing building could be in any of the Swiss seismic zone, computations were done for each zone and each ground class, i.e. 20 different cases. For each zone, a typical hazard curve from Giardini et al. (2004) was used.
Fragility curves were computed following Oropeza et al. (2010a,b) but using the elastic spectral displacement as a shaking parameter.
Moreover, its compliance factor was computed in force and in displacement following standard methods: the equivalent force method and Lang (2002) displacement-based method.

Table 4.1. Characteristics of the study-building including fragility medians and standard deviations

Name	City	Structural system	Floors	Freq. (Hz)	μ_{DG4} (cm)	σ_{DG4}	μ_{DG5} (cm)	σ_{DG4}
Chateauneuf 1	Sion	URM (stone)	stiff	1.58	2.4	0.62	2.9	0.70

4.2 Risk results

The probability density function of death as a function of PGA and return period is displayed on Fig. 4.1 for this structure (Zone 3b, soil class C). It shows the risk is especially carried by relatively low PGAs, due to the fragility of the structure. When the hazard increases, the total risk increases. Increasing the displacement capacity of a structure, for example thanks to a retrofit, moves the peak risk to higher PGA values and decreases its peak value and therefore the total risk. Moreover, the peak risk occurs for PGA values lower than the median fragility. Therefore, the standard deviation of the fragility curves appears to play a key role: high standard deviations, supposed to traduce our lack of knowledge of the structural behaviour, leads to much higher risk values.
Moreover, it is clear that a part of the risk is carried by very long return period ground motions (tail of the distribution) for which our knowledge is very uncertain. For buildings with a higher capacity, in such a moderate seismic country, this part becomes very important. Since buildings are considered to be built for 50 years, should ground motions events with such return period be considered in a code for existing buildings?

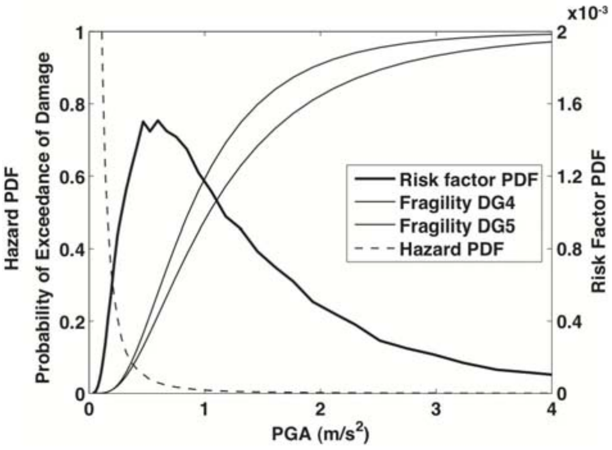

Figure 4.1 Individual risk probability density function as a function of PGA for the study-building.

The total risk, i.e. integrated on all the ground motion amplitude appears to be very large compared to what was expected (2.10^{-3} here). Indeed, considering Switzerland with 7 millions inhabitants on the 1000 last years, an individual risk of 10^{-4} would roughly correspond to 700 000 fatalities in 1000 years, an individual risk of 10^{-6} would be 7000 fatalities in 1000 years, which sounds more reasonable (Basel 1356, 300 fatalities, estimation for the same event today 12000 fatalities). The study-building is typical for Switzerland and other buildings showed comparable results.

There is therefore either an overestimation of hazard or an underestimation of capacity, or, more probably, an underestimation of the complexity of the phenomenon that does not allow the combination of the provided hazard and the computed vulnerability.

Table 4.2. Uncertainties on the results for the study-building.

Source	Hazard curve	Surface effects	Period	Median fragility	Fatality rates (x,y)
Type of uncertainty	Provided by PSHA	Roughly estimated from literature	Default value 10%	Default value 30%	From literature
Average ratio mean over extreme value	3.3	2.2	1.2	1.6	1.8

Table 4.2 summarizes the uncertainties accounted for in this study. The way they have been estimated (more or less relevant) is also reminded. The average ratio between the mean value and the computed extreme values (min and max) are displayed. Hazard plays the most important role in such estimation, showing the largest uncertainties for PSHA (more than 3 times between average and max for example) and surface effects. However, vulnerability is also a large source of bias. Indeed, there is no clear agreement in mechanical-based fragility, i.e. significant divergences are observed between curves proposed by HAZUS (FEMA, 2003) and those from Risk-UE (Milutinovic and Trendafiloski, 2003) for similar types of buildings. While comparing our results with the example of McGuire (2004), the greatest effects come from fragility curves since HAZUS curves for URM allow 6 times the displacement found here. Moreover, the uncertainties in the estimation of fragility curves are not determined in the computation and were probably underestimated here.

4.3 Risk vs. compliance factor

The curve representing the individual risk as a function of the compliance factor computed with a force-based method is represented on Fig. 4.2a with its uncertainties for the study-building. Similar results were found for other structures. As explained above, risk is found to be much higher than expected. Whatever the tuned parameter, SIA 2018 curve is in the lower bound. One of the possible explanations, as for the individual risk itself, for these too high values are larger probabilities for high return period ground motions compared to SIA 2018 hazard and bias in the vulnerability. Another source of differences is the assumed compliance factors for the different vulnerability classes in SIA

2018 sources. They seem quite pessimistic compared to the experience that has now been acquired. This should be investigated in more details.

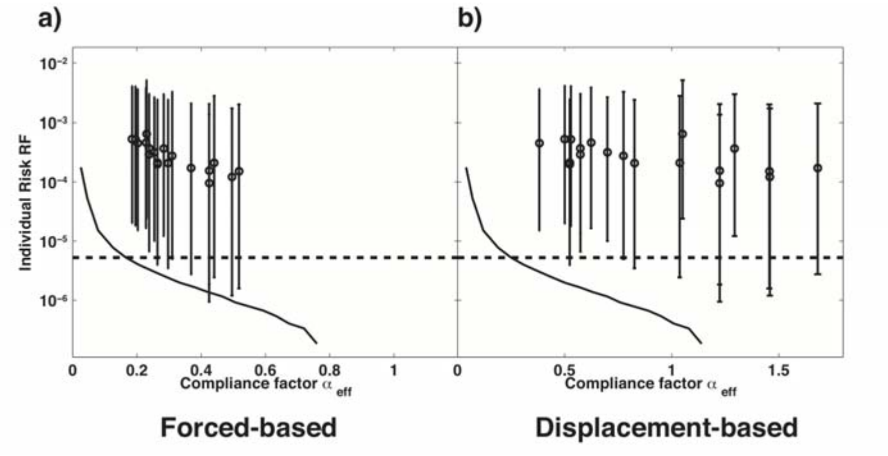

Figure 4.2 Individual risk as a function of compliance factor and comparison with SIA 2018 curve. Compliance factor computed using a) a forced-based method b) a displacement-based method. Dashed line is the accepted risk in SIA 2018.

Another important point is the use of force-based or displacement-based methods to compute the compliance factor. Fig. 4.2 shows also the comparison between force-based and displacement-based methods for the computation of the compliance factor. It is obvious that the 10^{-5} risk limit requires a much higher compliance factor computed with displacement-based methods. Since the SIA 2018 method is based on this limit on the risk, the compliance factor should theoretically not be computed using another technique than the one used to develop the risk/compliance factor relationship.
Since displacement-based method provide best-estimate values (and not conservative) for displacement capacity, and seems relevant to use them as the median of the fragility curve for the near-collapse damage grade. However, this means that, for this displacement value, the structure has 50% chance of collapsing. A structure can therefore be computed having a compliance factor of 1 using a displacement-based method and still have 50% chance to collapse for the design motion. Therefore, the precision of the used method has to be coherent with the one used in the design of the SIA 2018.

5 CONCLUSIONS

The Pre-Standard SIA 2018 is a very important normative tool to encourage owners to assess the vulnerability of their existing buildings and there is no doubt it will decrease the vulnerability of the Swiss building stock in the next 50 years.
However, it seems difficult with the current seismological and structural data to show that the chosen limits for the compliance factor are adequate considering the decided individual risk threshold.
As already shown by Grossi (2000), risk assessments are very uncertain and hazard assessment is the most uncertain part of the assessment. However, mechanical-based fragility curves are very different from one project to another and are also a large source of bias.
Moreover, displacement-based methods should be applied with care in the frame of SIA 2018 methodology since it has been designed assuming compliance factors computed with force-based methods.

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